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Shape Optimization with Surface-Mapped CPPNs

Daniel Richards and Martyn Amos

Abstract—Shape optimization techniques are becoming increasingly important in design and engineering. This growing significance reflects the need to exploit advances in digital fabrication technologies, and the desire to create new types of surface designs for various engineering applications. Evolutionary algorithms offer several key advantages for shape optimization, but they can also be restricted, especially as design problems scale up in size. A key challenge for evolutionary shape optimization is to overcome these challenges in order to apply evolutionary algorithms to large-scale, "real-world" engineering problems. This paper presents a new evolutionary approach to shape optimization using what we call "surface-mapped CPPNs". Our method outperforms a state-of-the-art gradient-based method on a simple benchmark problem, and scales well as degrees of freedom are added to the design problem. Our results demonstrate that surface-mapped CPPNs offer practical ways of approaching large-scale, real-world engineering problems with evolutionary algorithms, opening up exciting new opportunities for engineering design.

Index Terms—Shape optimization, engineering design, generative encodings, optimization methods, CPPN-NEAT.

I. INTRODUCTION

The recent proliferation of digital fabrication technologies (such as 3-D printing) has generated growing interest in high-performance *shell structures* and mechanically motivated surface designs [1]-[7]. *Shape optimization* techniques are a central component of this research field, and are used to produce high-performance designs according to precise requirements.

Shape optimization consists of three key elements. First, *geometry* of a 2-D or 3-D design is modeled so that all degrees of freedom are identified and parameterized. Second, the design is *meshed* (i.e., discretized) to ensure it is suitable for analysis and simulation (e.g. flow solver or structural analysis). Finally, an *optimization* process is used to manipulate the parameterized mesh design according to some objective function. Today, both gradient-based treatments and evolutionary algorithms are used in shape optimization.

Gradient-based methods are used across a wide range of structural optimization problem domains, including shape optimization, [1], [2], [8], [14], [34]-[38]. The general principle is to iteratively simulate the mechanical performance of an object, perform a gradient sensitivity analysis, and determine a series of geometric adaptations that will improve the engineering design in relation to the objective function [8]. When the design problem is (or can be made) convex, gradient-based methods work well, and converge to *optimal* solutions in good time.

Evolutionary algorithms (EAs) are also applied to shape and structural optimization, particularly in fields such as aeronautical and aerospace engineering (see [9] for an extensive review). Aeronautical applications of shape optimization techniques include next-generation airplane wings [10] and structurally robust monocoque shells [4], but these methods are also now being applied to architectural design in order to create large-scale, efficient, free-form structures [2]. This broadening in application is largely due to the increased availability of easy-to-use software packages, combined with affordable new fabrication processes [11].

As outlined in [9], EAs offer several key advantages for shape and structural optimization, compared to gradient-based numerical optimization methods. Two key advantages are (A) the ability to deal with *complex multimodal design spaces* and *highly nonlinear objective functions* (which are common in real-world problems), and (B) *ease-of-use* by designers and non-specialist engineers.

However, these advantages come at a cost. EAs are more computationally expensive than gradient-based methods, due to the bottleneck imposed by having to evaluate populations of solutions. Additionally, EAs do not *guarantee* convergence to optimal solutions and they often scale poorly. Consequently, evolutionary approaches are often limited to exploring relatively trivial benchmark problems with coarse discretization (i.e., with few degrees of freedom) and described using relatively few design variables.

This inability of EAs to deal with large-scale structural optimization problems and generate useful solutions within acceptable timeframes has led to criticism [12]. Consequently, *state-of-the-art* shape optimization methods generally comprise *gradient-based* approaches that employ a variety of sophisticated filtering techniques that help to convexify noisy search spaces and ensure successful convergence to optimal solutions [1], [2], [12]-[14].

In both gradient-based and evolutionary approaches, the way that geometry is modeled and *parameterized* plays a crucial role in the optimization process. Specifically, designs described by too few *parameters* (i.e. degrees of freedom),

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tend to converge quickly to sub-optimal solutions, due to the *low-resolution* nature of the parameterization. On the other hand, designs defined by relatively many parameters (i.e. more degrees of freedom) can often converge to superior solutions, due to the expanded space of possible shapes. However, in order to do so, they usually require many more evaluations, and thus use significantly more computational resource in the process.

In order to address this challenge in practice, designers often *manually* test various different parameterizations of problems in order to find the best solutions [13]. However, this process is time consuming and labor intensive, and is further compounded for evolutionary models, which typically need many more evaluations to solve similar problems. Indeed, this scalability challenge usually renders evolutionary methods unusable when shape optimization problems are described by many degrees of freedom [9], [12]. One route towards scaling up EAs for large-scale shape optimization problems may lie in *alternative chromosome encodings* [9], but further work is required.

In this paper, we present a new (gradient-free) evolutionary method, which we call *surface-mapped CPPNs*, and which is able to deal with large shape optimization problems with many degrees of freedom.

We first show that our approach can produce solutions with mechanical performance that is superior to that of solutions produced with state-of-the-art gradient-based methods, and then demonstrate that our method eliminates the mathematical challenge of scalability. To support these claims, our first experiment uses a well-known benchmark problem to compare the *physical properties* of solutions found by both state-of-the-art gradient-based methods and surface-mapped CPPNs. We validate these results to show that our evolved solutions are both reliable and mesh-independent. The second experiment then tests our surface-mapped CPPN on the same benchmark problem, but this time uses eight different parameterizations. This demonstrates that instances do not become more difficult to solve as more degrees of freedom are added to the design problem. When combined, these results demonstrate a powerful new approach to shape and shell optimization that is especially well-suited for exploiting digital fabrication technologies in high-performance engineering design.

The paper is organized as follows: we begin by discussing related work. We then outline our new method, describe the base experiment and validate these results, before presenting a second experiment to demonstrate the scalability of our approach. Finally, we conclude with a discussion of our results, and highlight further opportunities for development.

II. BACKGROUND

EAs offer several key advantages for engineering domains, but further work is needed to develop *alternative chromosome encodings* if they are to be competitive with state-of-the-art gradient-based methods [9]. Typically, chromosomes used in shape optimization consist of vectors of either real or binary numbers that describe transformations of individual vertex positions in 2-D or 3-D geometries (e.g. [1], [4], and [15]). The problem with this approach is that as designs increase in size and complexity, the chromosome encodings also become

much larger (due to the direct nature of the one-to-one mapping) and this significantly expands the search space, making it harder to find good solutions. Real-world shape optimization problems can easily comprise thousands of vertices, and encoding schemes are needed that allow for more effective search of these vast spaces. This scalability challenge is well-known in the evolutionary computing community [16] and is the subject of much research. To improve how EAs perform on large-scale problems, several techniques may be employed.

Firstly, to limit computational expense of simulating large populations of possible solutions, variants of *Evolutionary Strategies* are often used [9], [17]. These techniques demonstrate good convergence speed with small population sizes, and in doing so significantly improve how EAs scale. However, they do not *eliminate* the underlying problem, and are thus still susceptible to scalability challenges on large-scale problems [12].

A second approach to improving scalability is to limit the *dimensionality* of the search space. This may be achieved by exploiting *a priori* domain-specific knowledge of the design problem, and thus identifying only the important parameters to use in the shape optimization procedure. For example, when optimizing solutions that require fine-grained meshes, a common approach used by both EAs and gradient-based methods is to apply a series of *control points* to the original geometry, and define the position of each individual mesh vertex in relation to changes to a smaller number of specific control points. In this way, the shape optimization algorithm manipulates the positions of only the control points, allowing for a significant reduction in the dimensionality of the search space [18], [19]. The benefit of optimizing compact parameterizations lies in the fact that the system generally converges quickly. However, for this approach to work, the *correct* identification and parameterization of all control points are crucial. Consequently, for problems where comprehensive domain knowledge is *not* available in advance (which is usually most of them) this method has limited practical value.

Thirdly, *adaptive parameterizations* may offer a valuable trade-off [10], [20], [21]. Here, solutions begin as low-resolution parameterizations (with fixed mesh discretization), and, throughout an optimization process, designs *accrue* new degrees-of-freedom in order to incrementally build higher resolution parameterizations. The benefit of this approach is that it eliminates the most time-consuming part of traditional shape optimization methods (i.e. when performance of the solution is low and the dimensionality of the problem is high). By incrementally adding degrees-of-freedom to the model, solutions initially converge much more quickly, yet also retain the capacity to exploit higher parameterizations later on. This allows for the fine-tuning of geometric features and the creation of better performing designs [10]. Adaptive parameterizations have been applied to both evolutionary methods [17] and state-of-the-art gradient-based approaches [10], [20], [21], and have demonstrable performance benefits. However, there are also several key limitations of this approach: (A) the rate at which new degrees-of-freedom are added to designs plays a key role in the efficiency of the approach [21]. The implication is that specialist knowledge is

required in order to manually test and calibrate this new system parameter for each new problem, which is time consuming, labor intensive, and impossible for non-specialists.

(B) It is unclear how well this approach works on highly *non-convex* problems, which are characterized by deceptive design spaces.

(C) The ability of this approach to scale up to extremely large problems has yet to be demonstrated. To date, existing work using this approach has been limited to the addition of 20-30 parameters to solutions over the course of an optimization process [17], [20]-[21]. But real-world problems can easily contain thousands of degrees-of-freedom, and this number is growing alongside the geometric freedom offered by advanced fabrication technologies [2], [5], [9].

Ultimately, adaptive parameterizations provide a trade-off whereby a designer may make an educated initial guess as to which parameters are critical, and then use the algorithm to adjust this identified parameterization throughout the optimization process. However, as we argue throughout this paper, significant progress in this area can only be made when the parameterization of geometry is *independent* of the dimensionality of the search space.

Outside the scope of typical shape optimization methods, the area broadly defined as *generative and developmental systems* focuses on the capacity to evolve complex solutions from extremely compact encodings [22]. This paper will demonstrate that specific ideas, which have emerged from this area in recent years [23]-[28], have the potential to significantly advance engineering design through powerful new shape optimization techniques.

Our central insight involves changing the way that shape optimization problems are *conceptualized*. The key is thinking in terms of *patterns* instead of *points*. The traditional view of shape optimization problems is to view solutions as large collections of *points* that are individually adjusted in order to improve the performance of a design. The problem with this perspective is that each point is usually described by an individual optimization variable, and this means that solutions with *many* points are required to solve high-dimensional problems.

However, if we step back and view solutions as *functional patterns* painted across surface-conformed canvases, then the problem becomes conceptually much easier to solve. Indeed, from this perspective, the resolution of the canvas (i.e. number of vertices on the surface) may be independent of the *functional* description of the pattern (i.e. a mathematical function). This means that the traditional scalability problem can be eliminated, because the *parameterization* of the problem and the *dimensionality* of the search space are no longer explicitly linked.

To shift our thinking from the manipulation of individual points to instead *painting* functional patterns across geometry, we build on a rich body of work relating to the *NEAT* (Neuroevolution of Augmented Topologies) model [23] and *CPPNs* (Compositional Pattern Producing Networks) [24] [25], [26].

In 2007, Stanley [24] demonstrated that CPPNs can paint functional patterns across 2-D (pixel-based) canvases and be evolved with NEAT [23] to discover novel pictures. This idea is perhaps best demonstrated with Picbreeder [25], an online

tool where users collaboratively evolve populations of 2-D images. Following these 2-D demonstrations, Clune and Lipson [26] extended the idea of Picbreeder to evolve 3-D objects that can be fabricated with 3D printing technologies. In recent years, CPPN-NEAT has been used for a variety of applications, including evolving virtual [29], [30] and physical [31] creatures with diverse locomotive behaviors and dynamic properties [32], topology optimization [33], simulation of multi-material objects that exhibit higher-level behaviors such as specific deformations of 3-D beams [34] and vibrational frequencies [35], and evolution of efficient truss designs [36].

We suggest that CPPN-NEAT methods offer vast potential for shape optimization. However, in order to unlock the power of CPPNs for real-world optimization problems, it is necessary to resolve a key limitation of existing approaches. 3-D CPPN models have, to date, been almost exclusively used to control properties of volumetric pixels (or “voxels”) within traditional Cartesian (x,y,z) grids. From an engineering perspective, this approach has limited *practical* value. This is because real-world engineering problems typically require manipulation of *pre-defined* shapes and geometries, which are also subject to various physical constraints.

To address this challenge, Clune *et al.* [37] created a novel method of “seeding CPPNs” with geometric information associated with predefined shapes. The approach begins with a normal 3-D CPPN setup, whereby a 3-D array of voxels is set within a Cartesian grid, and a CPPN defines the property of each voxel as a function of its Cartesian (x,y,z) coordinate values. The key innovation of this approach (as described [37]) is to place a 3-D shape within the Cartesian voxel grid, and to then add an additional input to the CPPN, which inputs the distance between each voxel and the nearest point of the 3-D shape. By seeding a CPPN with geometric information about a predefined shape, Clune *et al.* show that it is possible to upload a voxelized version of the original 3-D shape, and then evolve it using the NEAT algorithm.

This approach to *seeding CPPNs* is potentially valuable for exploring conceptual 3-D designs. However, from an engineering design perspective, we argue that it is limited in specific ways.

A major problem is that designs produced with this method are often impossible to build (for example, featuring disconnected parts that “float” in space). Critically, most engineering design problems demand that specific constraints are enforced, e.g. all points on the surface of an object might need to be constrained to only move in one direction, or by a maximum distance. To our knowledge, seeded CPPNs are unable to deal with this sort of design constraint.

Another issue specific to shape optimization is that the geometric patterns and regularities, which feature in many solutions, are probably expressed much more easily as 2-D patterns mapped across curved surfaces than as 3-D patterns which define all solid and void voxels within a larger (and computationally expensive) 3-D array of voxels. Indeed, the ability to exploit a *surface-mapped* coordinate system may provide more useful compositional information relating to the design problem.

Our approach precisely exploits this insight. Specifically, rather than *seeding a CPPN* with geometric information that

relates to an object in Cartesian space, our approach may be conceptualized as wrapping a volume around a 3-D object and then *mapping* all inputs of the CPPN to suit a new object-based coordinate system.

The first major contribution of this paper is to show how our approach can unlock the power of CPPNs for real-world shape optimization problems. The second main contribution is to show how surface-mapped CPPNs can *scale up* and deal with truly large-scale problems, thereby eliminating the long-standing scalability challenge associated with evolving shapes with many degrees of freedom.

III. BASE EXPERIMENT

A. Methods

CPPN-NEAT has been previously described in detail [22]-[37] so here we provide only a brief summary, and focus on how our proposed method differs from existing versions. CPPNs are similar to neural networks, but the neurons in a network may contain a *variety* of different activation functions, and may be evolved with NEAT [23]. CPPNs query a discretized spatial domain by inputting the *positional information* (e.g. (x,y,z) coordinates) of each element and returning values that determine specific *properties* of that element (e.g. color). Through this process CPPNs can control grids of pixels and voxels to create 2-D and 3-D patterns. CPPNs can create a vast array of diverse patterns using compact encodings, and the patterns produced display geometric regularities, symmetries and even imperfect symmetries due to periodic activation functions within the CPPN (e.g. *cosine*) [24].

The key difference in our model is that we use CPPNs to paint patterns across *Non-uniform Rational Basis Spline* (NURBS [38]) surface domains (Fig 1). NURBS surfaces are commonly used to model geometry in design and engineering software packages. A useful property of NURBS surfaces is that any point can be located on the surface using a *relative* (U, V) coordinate system that extends from $(0, 0)$ to $(1, 1)$. As shown in Figure 1, we can exploit this relative coordinate system to build a new *surface-mapped* domain that is "clamped" between $(-1, -1)$ and $(1, 1)$. We can then discretize any NURBS surface, query each point by feeding its (U, V) coordinates into a CPPN, and then use the output value (Z^N) as the distance by which to move the queried (U,V) point relative to its surface normal. Following placement of surface nodes, we mesh the solution to create a shell with specific thickness, and export this information for structural analysis using a commercial *finite element analysis* (FEA) solver.

We refer to this approach as *mapping* a CPPN to a predefined NURBS surface. Our choice of terminology is intended to provoke analogies with conceptually similar techniques in computer graphics - specifically, techniques such as *texture mapping*, *bump mapping*, *normal mapping* and *displacement mapping* that are used to *paint* textures across geometry in computationally efficient ways. Indeed, our surface-mapped CPPNs operate in a similar manner, allowing us to paint geometric and material transformations across geometry, yet they can also be evolved with NEAT to discover mechanically motivated surface designs.

1) Benchmark Setup

To test our *surface-mapped CPPNs*, we use the simple benchmark problem originally proposed in [39], and more recently extended by [13], to demonstrate the performance of their sophisticated FE-based parameterization scheme in combination with the state-of-the-art gradient-based method: *SIMP* (Solid Isotropic Material with Penalization) [40].

We choose this benchmark problem for three key reasons. First, as discussed by [41], this problem is "highly non-convex", and state-of-the-art shape optimization methods reach local optima defined by an engineer's initial choice of a "sensitivity filter size" [13]. Second, this problem has been widely published in recently years [13], [41]-[44], and consequently we have good data with which to make comparative analyses. Finally, this benchmark problem has over 1,000 finite elements (FE) and comprises 1,736 degrees of freedom, which makes it challenging to solve with traditional *gradient-free* methods [12].

The goal of the benchmark problem is to stiffen a bending dominated L-shaped cantilever (Fig 2). Stiffening is achieved by moving FE-nodes relative to the surface normal and creating structural beads that are subject to a maximum bead height. The cantilever is made of steel ($E=210\text{GPa}$ and $\nu=0.3$) and has a thickness of 0.5mm. The structure is fixed at the top left and right corners, and is loaded with a single load of 5N, as shown in Fig. 2. The optimization variables are the set of *heights* of all FE-nodes relative to the surface normal. These variables are continuous, yet clamped between zero and the maximum bead height of 2.5mm. The objective is to minimize displacement experienced at the point on the L-shaped structure where the 5N load is applied (see Fig 2).

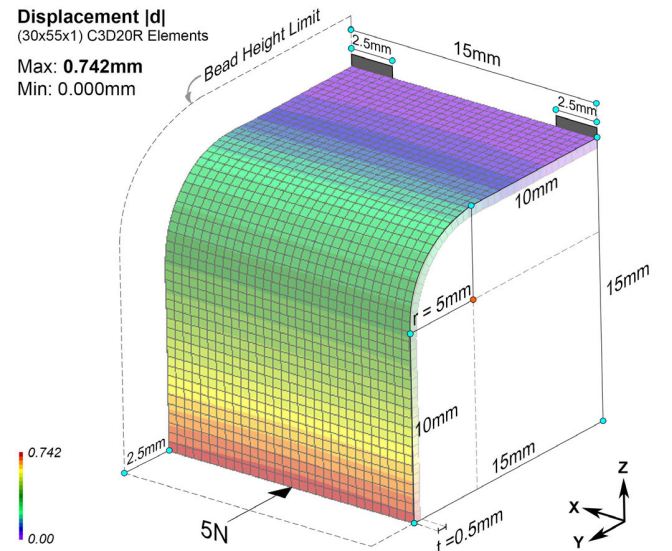


Fig. 2. Benchmark Problem Setup. This L-shaped cantilever shape is the NURBS substrate in our model. The cantilever is fixed at the top right and left corners within 2.5mm of the edges and loaded at the center of the lower flat part of the structure with 5N. As noted by Firl *et al.* [13], this loading acts in the x-axis and results in a bending load of the whole structure. The shell thickness is 0.5mm and the maximum bead height is 2.5mm. We use 1,650 C3D20R elements $(30 \times 55 \times 1)$ and record an initial displacement, $|d|$, of 0.742mm with this setup, as recorded by [13]. As shown in bottom left of the figure, the colors of the surface represent different amounts of displacement $|d|$ of the structure due to the 5N load.

We perform our finite element calculations using the open-source solver CalculiX, and use C3D20R elements, which are common across a variety of commercial FEA packages and perform well in bending. For the shape functions of C3D20R elements, see [45].

2) NEAT Setup

We perform 10 independent runs, each with a population of 100, evolved for 160 generations. We use our own Java implementation of NEAT with the following activation functions: *Gaussian*, *Sigmoid*, *Sine*, *Cosine* and *Linear*, all with an equal probability of being selected. We promote 25% of the population using mutations (i.e. no crossover), and for the remaining 75% of the population there is an 80% chance of mutating individuals after crossover. Mutation rates are 0.03 for adding a new node, 0.05 for adding a new link, 0.8 for perturbing a connection weight, and the probability of interspecies mating is 0.001. We use a dynamic compatibility threshold, the target number of species is 8, the initial species delta is 4, the niche size required for elitism is 5. Finally, the compatibility coefficients are $c1 = 1.0$, $c2 = 1.0$, $c3 = 0.5$. For a full description of the NEAT parameters see [23].

3) Fitness Function

To maximize stiffness of the cantilever, we minimize displacement experienced at the loading node. We calculate the magnitude of displacement as:

$$|d| = (ux^2 + uy^2 + uz^2)^{1/2} \quad (1)$$

Where: $|d|$ is the magnitude of displacement, ux is absolute displacement in the x-axis, uy is absolute displacement in the y-axis, and uz is absolute displacement in the z-axis. NEAT is a maximization algorithm, so we define our fitness function as:

$$\max \frac{1}{|d|^2} \quad (2)$$

B. Results

1) Comparative Analysis

We compare our results with those described in [13], which uses the (current) state-of-the-art (gradient-based) *Solid Isotropic Material with Penalization* (SIMP) method with a sophisticated FE-based parameterization scheme and sensitivity filter to address the same problem. This method produces high-performance solutions within about 30 optimization steps. Importantly, by varying the size of the sensitivity filter radius, the method converges to *different* local optima. This allows designers and engineers to run the model several times using a variety of different filter sizes in order to pinpoint the best performing solutions. The authors of [13] present results using three different filter sizes: 1mm, 2mm and 3mm, recording optimized $|d|$ values of 0.047mm, 0.033mm and 0.045mm respectively. These solutions represent significant improvements over the original geometry (0.742mm, as shown in Fig. 2). However, we now demonstrate that our surface-mapped CPPN method produces solutions with superior mechanical properties.

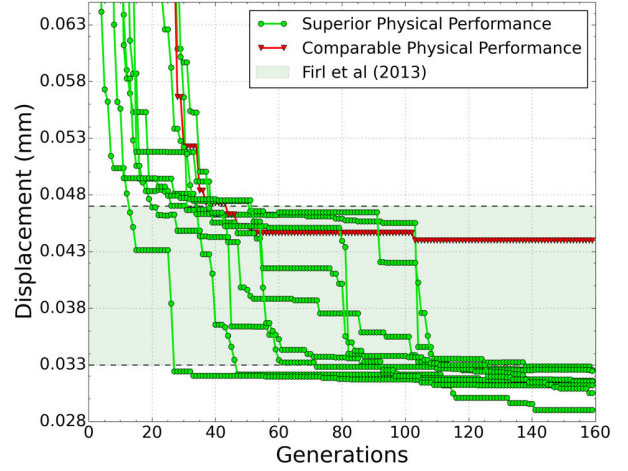


Figure 3. Performance of 10 runs of our model over 160 generations. Each line shows the best solution in the population at each generation (indicated by a point). 90% of our test runs discovered solutions, which outperformed designs created by Firl *et al.* [13] with state-of-the-art gradient-based methods.

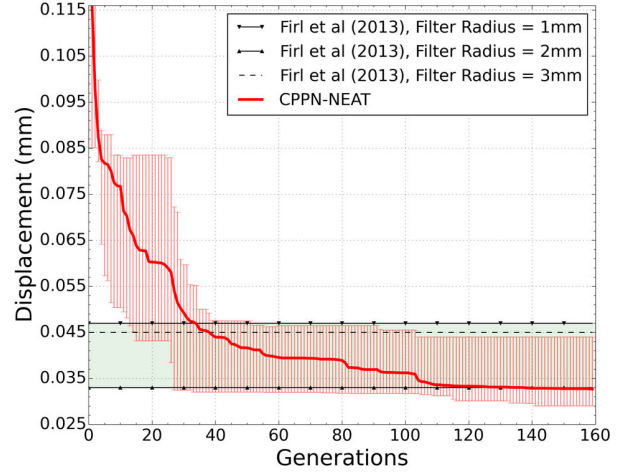


Figure 4. Mean convergence of the best solution in the population at each generation, over 10 runs. Also shown are the range of best solutions discovered at each generation over the 10 runs.

Fig. 3 shows the best solution in each population over 160 generations, for all 10 runs of our experiment. This convergence is plotted in relation to the range of solutions discovered by [13] using three different filter sizes. We outperform [13] in nine out of ten runs by discovering mechanically superior solutions that display less displacement of the structure under loading. Fig. 4 shows the mean convergence of the best solution in the population over ten runs, and demonstrates that we tend to converge to solutions that out-perform those described in [13] in relatively few generations. As shown in Fig 4, over 10 runs of the model, our average (mean) solution converges to a displacement equal to the upper limit of 0.047mm found by [13] within about 36 generations, and exceeds the best solutions found by [13] (0.033mm) within 139 generations. Fig. 5, shows three of our evolved solutions which exhibit superior mechanical performance than solutions found by [13] using state-of-the-art gradient-based methods.

2) Model Validation

We argue that our method is able to outperform state-of-the-art gradient-based methods in this problem domain because conventional sensitivity filters do not hamper our designs. Specifically, we think that the sensitivity filters, applied during gradient-based methods to (uniformly) smooth designs, actually *prevent* methods from discovering potentially useful *geometric features*. Since our evolutionary (i.e. gradient-free) approach does not need to calculate sensitivity gradients, it is not limited in the same way, and can therefore access and exploit geometric features that gradient-based approaches cannot. However, it is important to note that sensitivity filters are a well-established component of shape optimization, and fulfill multiple functions [14]. Consequently, to support the claim that our *unfiltered* solutions have superior performance, we first show that our solutions are valid.

As shown in Fig. 5A, when our FE-nodes move relative to the surface normal they cause our elements to stretch and produce slightly irregular meshes. Sensitivity filters are traditionally applied at this point to smooth mesh geometry and redistribute nodes, so that the size and shape of all mesh elements remain as uniform as possible.

This filtering process plays three key roles in gradient-based methods. Firstly, smoothing helps eliminate noise and ensures that gradient sensitivities are accurate during sensitivity analysis calculations. Secondly, the smoothed meshes help reduce numerical anomalies that can occur in FEA calculations due to distorted mesh elements. Finally, smoothing helps produce solutions that are *mesh independent* (i.e. that are not exploiting specific attributes of the discretization) and return the equivalent physical performance when simulated with finer meshes [13].

Since our evolutionary method does not require gradient information, we validate our solutions by showing that they are (A) not exploiting numerical errors caused by mesh distortion (i.e. not displaying deceptive physical performance), and (B) are mesh-independent.

Our FEA calculations use C3D20R elements, which are common quadratic brick elements with reduced integration points (2x2x2). C3D20R is a reliable and robust general-purpose element, and is not susceptible to numerical instabilities such as hour-glassing and locking phenomena. Consequently, a simple method of demonstrating validity of our method is to re-evaluate our final solutions with finer and more regular meshes (i.e. greater discretization of well-shaped C3D20R elements), and demonstrate equivalent results.

A novel property of the CPPN encoding is that the solutions theoretically obtain *infinite resolution*. That is, because CPPNs paint functional patterns across a NURBS-based substrate, the designs they encode are not limited to a fixed resolution. In order to increase the resolution of evolved solutions, we may simply increase the discretization of the NURBS substrate (in this case, the L-shaped cantilever shown in Fig 2), and re-query the CPPN to create high-resolution meshes. However, in contrast to sensitivity filters, which have a tendency to “over-smooth” geometric features, increasing the resolution of solutions discovered with surface-mapped CPPNs can have the inverse effect of “under-smoothing” evolved features and revealing geometric properties that were not apparent at the resolution originally used to optimize the design.

For example, consider a 2-D beam that has been evolved using our method, and is composed of only two horizontal finite elements. If the (continuous) CPPN output describes a Gaussian curve, then the discretized 2-D beam design (1x2 elements) will form an upside down “V” shape (Fig. 6). However, as we increase the resolution of the design by subdividing the domain and adding extra elements (e.g. 1 x 4 and 1 x 8), the solution begins to approximate the CPPN-generated Gaussian distribution, and thus the evolved upside-down “V” shape is lost.

To counteract the tendency to *under-smooth* solutions as mesh resolution is increased, we can apply a simple Laplacian smoothing filter (see [46] for an extended description of Laplacian smoothing). This has two significant effects. Firstly, the smoothing filter dramatically improves mesh regularity (as is known from traditional sensitivity filters), but secondly, it ensures that higher resolution designs closely approximate the original evolved design. To perform Laplacian smoothing, we re-query our evolved CPPN and define the height of each node using the average output of surrounding nodes within a Moore neighborhood of range, R :

$$\bar{h}(a, b) = \frac{1}{N(a, b)} \sum_{i=a-R}^{a+R} \sum_{j=b-R}^{b+R} H(i, j)$$

Where:

$$H(i, j) = \begin{cases} h(i, j), & \text{if } 0 \leq i \leq Ma \wedge 0 \leq j \leq Mb \\ 0, & \text{otherwise} \end{cases}$$

$$N(a, b) = \sum_{i=a-R}^{a+R} \sum_{j=b-R}^{b+R} n(i, j)$$

$$n(i, j) = \begin{cases} 1, & \text{if } 0 \leq i \leq Ma \wedge 0 \leq j \leq Mb \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

Where: $\bar{h}(a, b)$ is the average (Laplacian smoothed) height, h , of node (a, b) , R is the Moore neighborhood range, and Ma and Mb are the maximum number of nodes in the a and b dimensions of the mesh grid, respectively.

As shown in Fig. 6, the success of this method, when applied to CPPN generated outputs, relies on careful coordination between the Moore neighborhood range, R , of the Laplacian smoothing filter and the increased resolution size. For example, if we apply the Laplacian filter directly to the initial (1 x 2) 2D beam design (i.e. without increasing the mesh resolution) the shape quickly begins to approximate a flat line due to over-smoothing. However, if the Moore neighborhood is incremented each time the mesh resolution doubles, then we can avoid *over-smoothing* and *under-smoothing* (Fig. 6). This method allows us to produce finer resolution meshes that have significantly more uniform elements, yet - critically - they remain close approximations of the original evolved designs.

Fig. 7 shows the evolved design from Fig 5A, at three significantly different resolutions (1,650, 6,600 and 26,400 elements) and with different filter properties (i.e. no filter, $R=1$, $R=2$) to illustrate the percentage error and absolute error introduced to the FEA results following transformation. Here percentage error is defined as:

$$\% \text{ error} = \frac{|dx - \bar{dx}|}{dx} \quad (4)$$

Where: dx is $|d|$ experienced at the loaded node in the evolved solution (30 x 55 resolution, no filter), and \bar{dx} is the $|d|$ experienced by the updated solution.

As shown in Fig. 7, applying Laplacian smoothing directly to the evolved design has the effect of over-smoothing the evolved features, and altering mechanical performance. Note that while mechanical performance is worse, the shape and size of the mesh elements are significantly improved and made more regular. The central image in Fig. 7 shows the effect of doubling the resolution from (30 x 55) elements to (60 x 110) elements and applying a Laplacian smoothing filter with $R = 1$. Here we see a FE-mesh with significantly more uniform elements and only 0.4% difference in simulated performance. Similarly, we achieve a relatively small 3.7% error even as we multiply the number of mesh elements by a factor of 16 times (Fig. 8).

Figure 9 shows the results of testing all of our evolved solutions at differing resolutions and with different filter ranges. To compare our results we show our percentage error in relation to the results of [13]. The authors show that their solutions are *mesh independent* by altering the resolution of their mesh between 1,650 and 6,600 elements and re-running their gradient-based method to show that they converge on equivalent solutions with about 4 – 6.5% error. In comparison, we show an average error of 3.5% and 7% when increasing resolution to 6,600 elements and 26,400 elements respectively.

By showing that the mechanical performance of our evolved designs (Fig 5A) can be replicated using significantly finer and more regular meshes (Fig 7-9) and - importantly - using reliable C3D20R elements, we show that our method of evolving surface-mapped CPPNs is not exploiting mesh irregularities to produce deceptive results, and is indeed improving on state-of-the-art gradient-based methods for shape optimization. Specifically, we show that our method can consistently discover mechanical designs that are better than existing state-of-the-art methods [13].

IV. SCALABILITY EXPERIMENT

A. Modifications to Methods

To test the scalability of our method, we explore eight different parameterizations of the previous benchmark problem (Fig. 2), and use two different surface transformations. Firstly, we evolve designs with a uniform shell thickness. Secondly, we evolve designs where shell thickness is allowed to vary (locally) across the surface.

To build designs with *uniform* shell thickness, we use a CPPN (as before) with three inputs, and one output (see Fig 1). To build designs with *variable* shell thickness, we use the same CPPN method, but add an extra output, T , to control *shell thickness*. As shown in Figure 10, Z^N continues to define a surface extrusion relative to the surface normal, but now T defines the thickness of the shell across the surface. Here, T defines the thickness of the shell at each (u,v) coordinate on the NURBS substrate by locally extruding the shell in the opposite direction of the surface normal, ensuring that the minimum shell thickness at any point is 0.01mm and the

maximum is 1.0mm (Fig 10). The solution is then meshed and subjected to FEA as the uniform shell. Note that a key difference between the *uniform* and *variable* shell designs is the number of degrees-of-freedom.

1) Modifications to the Benchmark Setup

We add additional *degrees of freedom* (DoF) to the original benchmark problem in order to demonstrate that, unlike similar methods [4], [15], [17], the problem does not become more difficult to solve as more DoF are added to the system.

To demonstrate this scalable behavior, we increase the dimensionality of the problem in two specific ways, and test eight different parameterizations of the benchmark problem.

Firstly, we vary the *discretization* of the FE-mesh. Our base experiment used a fixed mesh resolution of 30 x 55 elements (i.e. 1736 different DoF). In this paper we test four different mesh resolutions: 6 x 12 elements (91 DoF), 12 x 24 elements (325 DoF), 24 x 48 elements (1225 DoF), and 48 x 96 elements (4753 DoF). Here each *uniform* shell has a fixed thickness of 0.3mm.

Secondly, we allow solutions to vary their discretization *and* shell thicknesses across the surface domain, subject to a maximum volume constraint. Here the local shell thickness is a continuous value between 0.01mm and 1.0mm. If the volume of the final shell solution, sV , is greater than a maximum volume, mV , the CPPN is re-queried and the thickness, T , of each point is scaled linearly to meet mV .

We calculate the volume of each shell solution by taking each finite element block (as shown in Fig 10), and splitting it into twelve irregular tetrahedrons. Each tetrahedron is defined by six edges: a, b, c, A, B, C , where the pairs (a,A) , (b,B) , and (c,C) are opposite edges that do not share common vertices (Fig. 11).

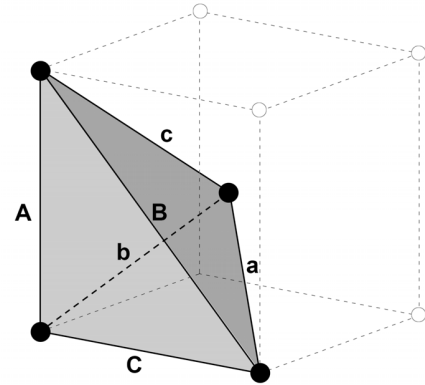


Figure 11. Irregular tetrahedron defined by six edges: a, b, c, A, B, C . The volume of each finite element block, as shown by the dotted bounding box, is calculated by summing the volume of 12 irregular tetrahedrons.

We calculate the volume of each tetrahedron, tV , as:

$$tV = \frac{(4a^2b^2c^2 - a^2a'^2 - b^2b'^2 - c^2c'^2 + a'b'c')^{1/2}}{12}$$

Where:

$$a' = b^2 + c^2 - A^2$$

$$b' = c^2 + a^2 - B^2$$

$$c' = a^2 + b^2 - C^2$$

(5)

We then calculate the volume of each shell by summing over all tetrahedrons:

$$sV = \sum_{i=1}^N \sum_{j=1}^{12} tV_{ij} \quad (6)$$

where: tV_{ij} is the volume of the j th tetrahedron within the i th finite element in a collection of N FE blocks.

To constrain sV of each shell to mV , we re-query the CPPN and linearly scale the shell thickness, T , to meet mV using:

$$\sum_{u=1}^{U_t} \sum_{v=1}^{V_t} r(T_{uv}, sV, mV)$$

Where:

$$T \in [0.01 : 1]$$

$$r(t, sV, mV) = \begin{cases} t, & \text{if } sV \leq mV \\ t \times (1 - mV/sV), & \text{if } sV > mV \end{cases} \quad (7)$$

where: T_{uv} is the local shell thickness generated by querying the CPPN at point (u, v) on the NURBS surface, and U_t and V_t are the total number of points on the NURBS surface in the u , and v dimensions respectfully. T_{uv} can have a minimum value of 0.01 and a maximum value of 1.0. In these experiments we set mV to 130mm^3 . Notably, shells with uniform shell thickness of 0.3mm have a volume that is between 124.2mm^3 and 141.9mm^3 (depending on how points are extruded to form structural beads).

The important consequence of using variable shell thickness is that it *doubles* the number of DoF in each parameterization of the benchmark problem. This creates eight different parameterizations with increasing DoF: 91 and 182 (uniform and variable shell thickness of discretization: 6×12), 325 and 650 (12×24), 1225 and 2450 (24×48), and 4753 and 9506 (48×96). These eight parameterizations allow us to test how our surface-mapped CPPN approach performs across a range of different scales.

As in our base experiment, we perform our finite element calculations using the open-source solver *CalculiX*, but this time we use *C3D8* elements. Our base experiment used *C3D20R* elements, which are robust and reliable FE brick elements, in order to compare our solutions with a state-of-the-art gradient-based approach [13]. *C3D20R* elements more accurately simulate physical behavior, but the trade-off for fine-grained analysis is increased computation time [45]. In this experiment we use *C3D8* elements, which are less accurate, but much faster to simulate and therefore allow us to explore the scalability of our approach in a reasonable timeframe.

2) Modifications to the NEAT Setup

We perform 20 independent runs of each of our 8 parameterizations, each run using a population of 100 solutions, evolved for 200 generations. All other details of the NEAT setup and fitness function are the same as in the base experiment.

Since we use different finite element bricks in this benchmark setup, our results are not directly comparable to solutions found in the base experiment. Consequently, our decision to increase the number of runs and generations is due to a desire to exploit the reduced runtimes of our simulations (when using *D3D8* elements) in order to provide a better picture of *average* convergence behavior across different parameterizations of the benchmark problem.

A. Results

We now present the results from eight different parameterizations of the benchmark problem. Our focus is on how designs *converge* as the benchmark problem increases in scale. Our results show that, in contrast to traditional shape optimization techniques, the benchmark problem *does not* become more difficult to solve as we increase the number of degrees of freedom. Indeed, our results show that the benchmark problem actually becomes *easier* to solve with higher resolution parameterizations.

We first test solutions with uniform thickness and varying mesh resolution. Figure 12 shows the mean convergence of the best solution in each population over 20 runs of the model. As shown, the lowest resolution FE-mesh (i.e. 6×12 elements) converges to a displacement, $|d|$, of 0.073mm after 200 generations. We then see that for each successive increase in scale, i.e. 12×24 elements, followed by 24×48 elements, we converge to better solutions, and this trend continues as we reach our highest resolution of 48×96 elements (4753 DoF), which achieved an average $|d|$ of 0.041mm.

Secondly, we test solutions with variable thickness and varying mesh resolution. Figure 13 shows the mean convergence of the best solution in each population over 20 runs. In a similar fashion to Figure 12, we see that higher resolution FE-meshes converge to solutions with mechanically superior performance (i.e. less displacement at the loaded node). On first sight, this finding is perhaps not completely surprising, as it is well-known that designs defined by more degrees of freedom can often discover better solutions, due to the increased opportunity for fine-tuning [21]. However, the key point is that this ability typically comes at a *cost* of many more evaluations and thus increased computational expense.

Indeed, designs with low resolution FE-meshes typically converge quickly to sub-optimal solutions, whereas whilst higher resolution FE-meshes can often find superior solutions, they require many more evaluations to converge [9], [10]. Figures 12 and 13 illustrate that solutions evolved with surface-mapped CPPNs are *not* subject to this behavior. In fact, we find that solutions controlled by more optimization variables discover superior solutions in *fewer* evaluations.

Figure 14 illustrates this by comparing the average number of generations required by each of the different parameterizations to converge to a specific displacement value. The specific displacement value chosen to act as a threshold for this comparison is 0.0609mm. This value was chosen because it represents the upper range of solutions discovered with the 6×12 variable shell solution (see Fig 13). Critically, this value represents an evolved solution with relatively few DoF (650) that is not *obviously* converging to sub-optimal solutions in the same way as the 6×12 uniform shell solutions (see Fig 12). Figure 14 shows that

parameterizations with both uniform and variable shell thicknesses converge to the threshold of 0.0609mm in fewer generations as more DoF are added to the solution. The significance of this plot is that traditional shape optimization methods produce the *inverse* effect – that is, as DoF increase, so do the number of generations required to converge [9], [21].

It is important to note that, in these experiments, higher resolution parameterizations take fewer *evaluations* to converge, yet do take more *time* to solve than lower-resolution designs, due to the increased computational expense of the FEA. This might initially appear to be an obvious limitation of our approach. However, in practice, approaches which employ strategies to reduce the dimensionality of the problem in order to improve speed of convergence do not change the resolution of the FEA mesh, but simply change the number of control points that define DoF in the model [2], [4], [17], [18]–[21]. Consequently, our finding that parameterizations with more DoF can discover superior solutions in fewer evaluations is potentially significant for shape optimization.

Next, we compare how uniform and variable shell solutions with identical mesh resolutions converge (Fig 15). We observe that more DoF lead to better solutions (i.e. less displacement) and faster convergence. Finally, Figure 16 shows the spread of mechanical performance achieved across the eight different parameterizations. This plot emphasizes our key finding, that evolving surface-mapped CPPNs for shape optimization does not become more difficult as more degrees of freedom are added to the system. In contrast, we find that problems defined by more DoF are consistently easier to solve and also converge to superior solutions in fewer evaluations. For raw convergence data collected from both experiments see: <https://dx.doi.org/10.6084/m9.figshare.3795888.v1>.

These results, in parallel with the findings from our base experiment, suggest significant potential for tackling complex and large-scale shape optimization problems using surface-mapped CPPNs.

V. DISCUSSION

Our results demonstrate that surface-mapped CPPNs offer practical improvements over state-of-the-art methods to shape optimization. In this section we discuss (A) the advantages of our approach in terms of the superior physical properties of solutions; (B) the ability to scale up and solve design problems with many degrees of freedom, and (C) exciting opportunities for further exploration.

A. Advantages Relating to Physical Performance

A significant feature of our method is that it does not *explicitly* define sensitivity filters. As evidenced by [13], [41]–[44], different filter sizes constrain state-of-the-art gradient-based methods to converge to specific local optima. Consequently, *filter size* becomes an important design variable that designers must experiment with to access different solutions within the search space. But once the filter size is set, it is *uniformly* applied to the mesh to smooth the design.

We claim that a key limitation of these state-of-the-art approaches is that a *combination* of different filter sizes,

applied simultaneously across the design may conceivably produce even better solutions than existing uniform filters.

This insight is the key to understanding *why* our surface-mapped CPPNs improve on state-of-the-art methods. Specifically, our approach uses CPPNs to paint functional patterns across NURBS geometry to create coordinated mesh transformations. Recall that the CPPN-generated patterns exhibit useful features such as geometric regularities with repeating motifs; symmetries and even imperfect symmetries; and thus the capacity to create both smooth gradations and more abrupt angular transitions between parts of the design. This means that our encoding can *implicitly* control smoothness of geometric features during evolution, and, critically, does so in a non-uniform manner that is not limited in the same way as existing state-of-the-art gradient-based methods.

A common criticism of *gradient-free* methods for shape and structural optimization is that is that they cannot *guarantee* that the solutions converge to the global optimum. This remains true with our approach. However as we have discussed, in state-of-the-art shape optimization methods, parameterization decisions involved in setting up sensitivity filters actively define which “optimum” is discoverable. Consequently, while our model cannot *guarantee* convergence to an optimal solution, we seem better able to approximate the *true* global optima than state-of-the-art methods, and in doing so, can discover solutions that have superior performance on highly non-convex, real-world problems.

A. Advantages Relating to Scalability

The results of our scalability experiment suggest that surface-mapped CPPNs enable a powerful and *scalable* approach to shape optimization. Critically, our choice of FE-mesh resolutions (6x12), (12x24), (24x48), (48x96) allow us to test our benchmark problem at a variety of significantly different scales, ranging from 91 to 9506 degrees of freedom. This increase in scale is *substantial* compared to related studies [2], [4], [9], [10], [17], [21], and also *significantly exceeds* the 1,000 DoF threshold which is known to be currently challenging for gradient-free methods due to the need to individually parameterize and manipulate each DoF [12]. However, we consistently discover superior solutions, in fewer evaluations, when using parameterizations with more degrees of freedom.

An interesting observation is that while our high-resolution (48x96) solutions with uniform and variable shell thickness converge to similar displacement, $|d|$, values, the physical properties of these designs are often very different (Fig 17). As shown in our base experiment, our evolved uniform shell designs tend to form angular structural beads. However, shell designs with variable thickness (subject to a maximum volume constraint) produce much more “organic” looking shapes. Indeed, these solutions tend to drastically reduce shell thickness in less important areas, whilst increasing shell thickness in areas of greater structural stress. This ability to exploit a range of geometric freedoms is particularly useful in engineering domains that can exploit emerging additive manufacturing technologies (i.e. 3-D printing) where manufacturing costs are typically defined by the *volume* of material used, rather than complexity of form.

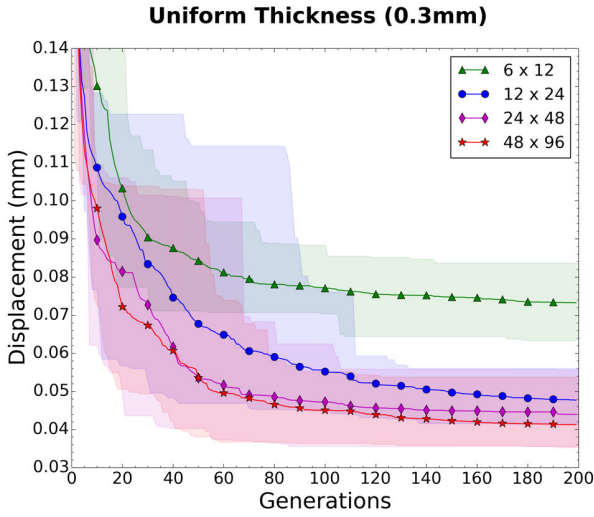


Figure 12. Convergence of uniform shell solutions with different DoF over 200 generations. Mean convergence, and variation of the best solution in each population across 20 runs are shown. Solutions defined by more DoF converge to better performing designs.

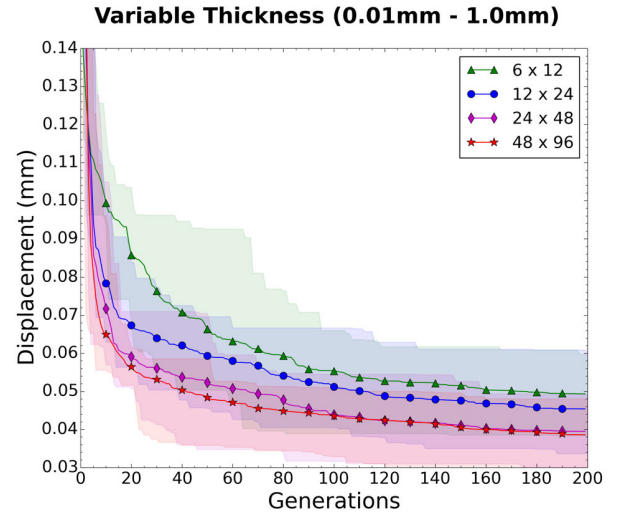


Figure 13. Convergence of variable shell solutions with different DoF over 200 generations. Mean convergence and variation of the best solution in each population across 20 runs are shown. Solutions defined by more DoF converge to better performing designs.

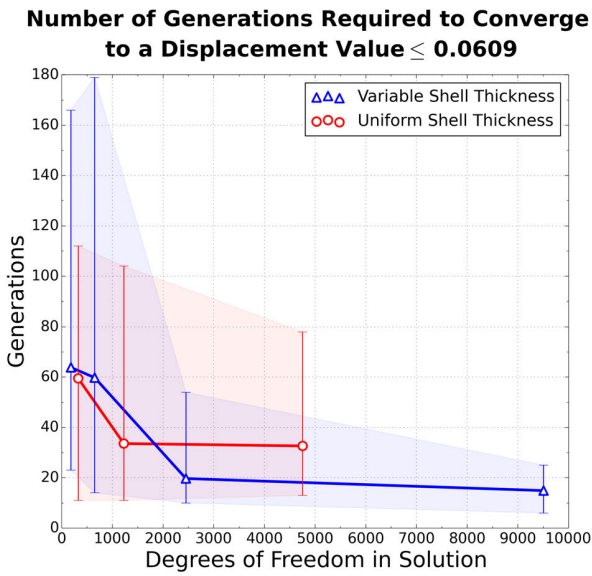


Figure 14. Convergence behavior of different parameterizations. Mean number of generations required to hit the threshold over 20 runs of the model is shown for each parameterization. Range of maximum and minimum generations required to converge to the threshold is also shown. Solutions with uniform shell thickness are plotted in red, and variable shell thickness in blue.

Critically, the shell designs with variable thickness do *not* use more material than those with uniform thickness (in fact, in some cases they use less); rather, they are afforded the capacity to *control* where material is transformed. This type of parameterization would traditionally be fraught with scalability problems, especially when using EAs, yet our surface-mapped CPPNs easily coordinate geometric transformations to find good solutions.

Another useful property of our approach is that it is conceptually relatively simple, and therefore (unlike adaptive parameterizations) does not require specialist knowledge to

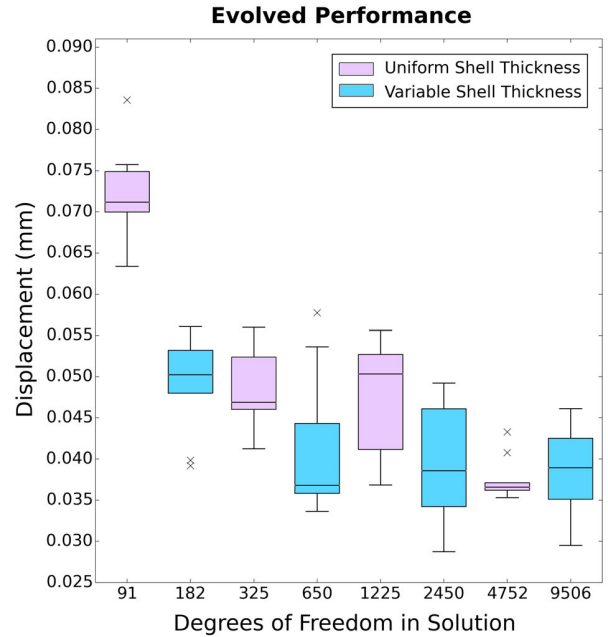


Figure 16. Spread of best evolved solutions from all 20 runs, over 200 generations each time, using different parameterizations. As the number of DoF increases, better solutions (i.e. those showing less displacement at the loaded node) are discovered more regularly.

tune newly introduced problem specific parameters. In terms of commercial application and use in industry, we suggest that this is a major advantage. Future work will explore this further.

The key reason why our approach performs well, and across scales, is that by changing how shape optimization problems are conceptualized (as *patterns* instead of *points*) we exploit a rich, seemingly untapped and *free* source of *compositional* information. Specifically, optimal solutions to shape optimization problems typically (if not always) exhibit *well-defined* and *coordinated* geometric features that are underpinned by geometric and spatial relationships. Yet, many

shape optimization methods ignore this fact, instead choosing to treat designs as collections of points, which are individually parameterized, manipulated and then post-processed to achieve smooth transitions and coordinated transformations.

By evolving surface-mapped CPPNs, we completely re-frame the problem, and in doing so make high-resolution geometric problems just as easy to solve as low-resolution geometric problems. That is, instead of conceptualizing shape optimization as a high-dimensional combinatorial optimization problem, where the exact value of each parameter is sought, our approach uses CPPNs to discover underlying geometric and spatial relationships that are often (if not always) present in these types of problems.

Critically, previous work relating to CPPN-based methods of generating 3-D objects has also demonstrated this ability to exploit free compositional information to create scale free geometric transformations. However, by mapping the spatial domain to specific surfaces – rather than using Cartesian volumes – we are able to exploit free compositional information relating to predefined geometries, while simultaneously enforcing much-needed constraints on engineering design problems.

In this paper we show that our approach is conceptually easier to use than similar methods (i.e. adaptive parameterizations), can produce superior mechanical solutions compared to state-of-the-art gradient-based approaches on a well-known benchmark problem, exploit the core benefits of evolutionary methods in terms of addressing complex multimodal problem domains, and – perhaps most importantly – operate well at large scales.

B. Opportunities for Further Work

We now discuss several key benefits and opportunities for progress in this area, as well as ongoing challenges that require further work.

Advanced digital fabrication technologies (e.g. additive manufacturing) are transforming construction. Not only do these technologies offer vast geometric freedom to designs, but also they allow us to combine *different materials* within single objects, and thereby construct complex composites with bespoke physical properties and behaviors. These technologies are opening up exciting possibilities for large-scale shell structures in design and engineering domains [2], bio-inspired composites [3], resilient high-performance shell designs [4], next-generation robotics [31], exotic compliant mechanisms and morphing structures [47], [48]. Evolutionary approaches, such as surface-mapped CPPNs, that can deal with large numbers of design variables and approximate optimal designs, will offer significant benefits for exploiting these new fabrication technologies by exploring highly non-convex and disjoint search spaces in response to ill-defined and multi-objective goals.

We conclude by outlining three areas for future research that we think will be valuable in leveraging surface-mapped CPPNs to advance engineering design.

Firstly, an ongoing challenge with our current setup is that it is computationally expensive. That is, while our model requires roughly the same number of *generations* as *optimization steps* required by [13] (i.e. to test all three filter

sizes), in order to discover superior solutions each generation requires an additional 99 FEA evaluation calls, due to the need to simulate populations of solutions. Consequently our simulation time is about 100 times that of [13]. For example, our base experiment, with 1,736 degrees of freedom, requires about 17 hours run time to process 160 generations, which is impractical for use within industry. However, we are currently running our model on a single PC. Further work is required to utilize cloud-based systems and evaluate individual solutions from each generation in parallel. This would drastically reduce the time required to solve design problems, make our method much more suitable for commercial application, and render it potentially comparable to gradient-based methods in terms of time required to generate solutions.

Secondly, as we demonstrate in our base experiment, in order to increase the resolution of evolved surface-mapped CPPNs and produce similar solutions, it is necessary to employ strategies that prevent under-smoothing and over-smoothing (Fig 6). In this paper we demonstrate a simple Laplacian smoothing operator in order to demonstrate that our solutions are mesh independent. However, further work is needed in this area to ensure that surface-mapped CPPNs can be reliably recreated at any resolution without further evolution. Additionally, while we show that surface-mapped CPPNs eliminate the need for adaptive parameterizations on large-scale problems, we suggest that there may be cases where designs benefit from mesh solutions that feature non-uniform discretization, or which perhaps feature adaptive mesh strategies [49]. Specifically, there may be times when it is easier to produce high-performance solutions with FEMs, which are subdivided and discretized differently. Notably, ES-HyperNEAT approaches [50] have proven useful in other domains, and may provide useful insights for further research in this area. Additionally, alternative methods of exploiting CPPN outputs may enable high-performance surface conformed truss and lattice structures [36], which may be advantageous in specific problem domains.

Finally, this paper demonstrates shape optimization on one benchmark problem only. To progress this proof-of-concept study, further work is needed to test this approach on a variety of different benchmark problems. Notably, the real benefit of using EAs, rather than state-of-the-art gradient-based methods, is that they can be applied to non-trivial design problems that are characterized by deceptive search spaces, for example, exotic compliant mechanisms, multi-material composites and shape changing structures. Further work will explore material maps as a method of addressing these sorts of *non-trivial* design problems, and fully exploit the benefits of evolutionary methods to advance engineering design.

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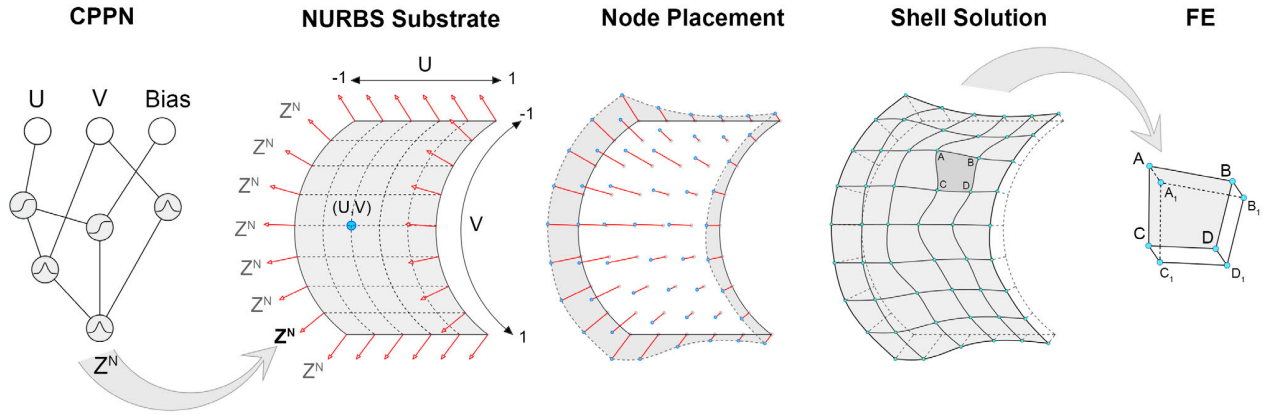


Figure 1. Surface manipulation process. Firstly, a CPPN queries each point within a NURBS-based substrate of specified discretization, and using the points (u,v) coordinates as inputs, returns a bead height (Z^N). Secondly, shell nodes are placed by extruding points in the direction relative to their surface normal by their CPPN generated bead height. Shell solutions are then created by meshing the nodes. Finally, solutions are broken down into finite elements (FE) for structural analysis. Here the shell thickness of each FE is defined by controlling the distance between nodes A and A_1 .

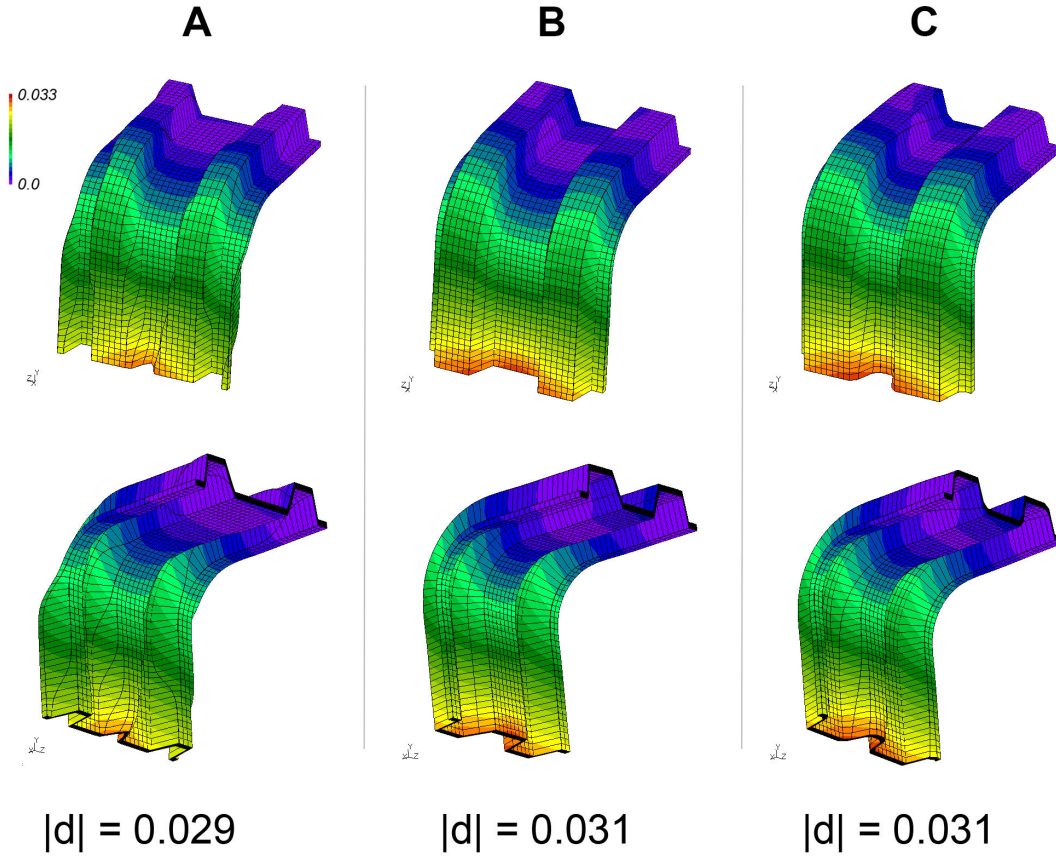


Figure 5. Three solutions to the benchmark problem which demonstrate superior mechanical performance by manipulating the original L-shaped cantilever shape, as shown in Fig. 2, using our surface-mapped CPPN method. Front and back views of designs are shown. The different colors represent different amounts of displacement experienced across the design. As shown by the key in the top corner, red shows displacement of 0.033mm, whereas purple represents zero displacement at that part of the structure. The absolute displacement values documented at the loaded node are indicated below solutions. As shown in (A), mesh elements are slightly irregular due to the way that nodes move relative to the surface normal. Specifically, we see some elements are long and thin, whilst others are squarer. Additionally, designs have areas with angular (non-smooth) features that traditional sensitivity filters would prevent (see [13]).

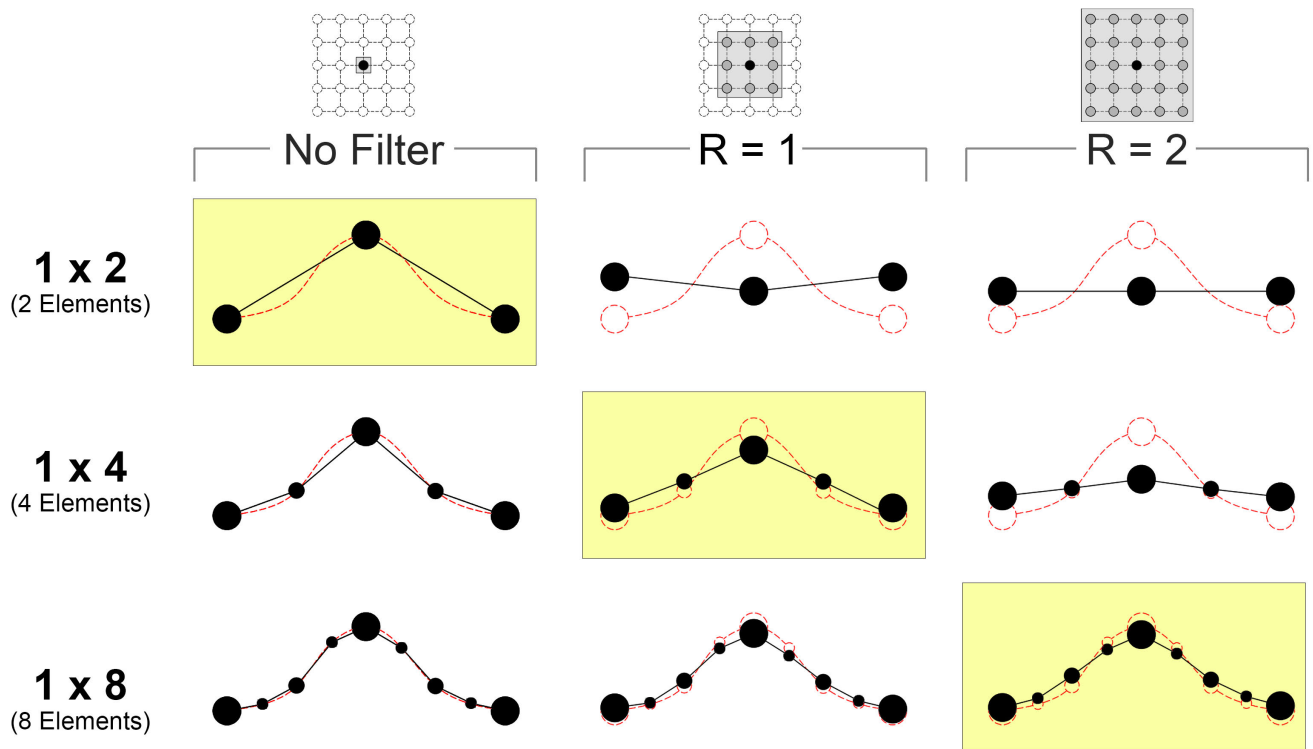


Figure 6. Influence of Laplacian smoothing on a toy 2D beam model. The red dotted line indicates the continuous CPPN output - a Gaussian function. Applying Laplacian smoothing to the 1 x 2 elements has the effect of over-smoothing the design and losing the original upside-down “V” shape form. Conversely, increasing resolution without applying smoothing leads to under-smoothing and losing the original shape also. By increasing the Moore neighborhood range, R , by one node for every time the resolution doubles, the “V” shape is conserved whilst the quality of the FEA domain is improved.

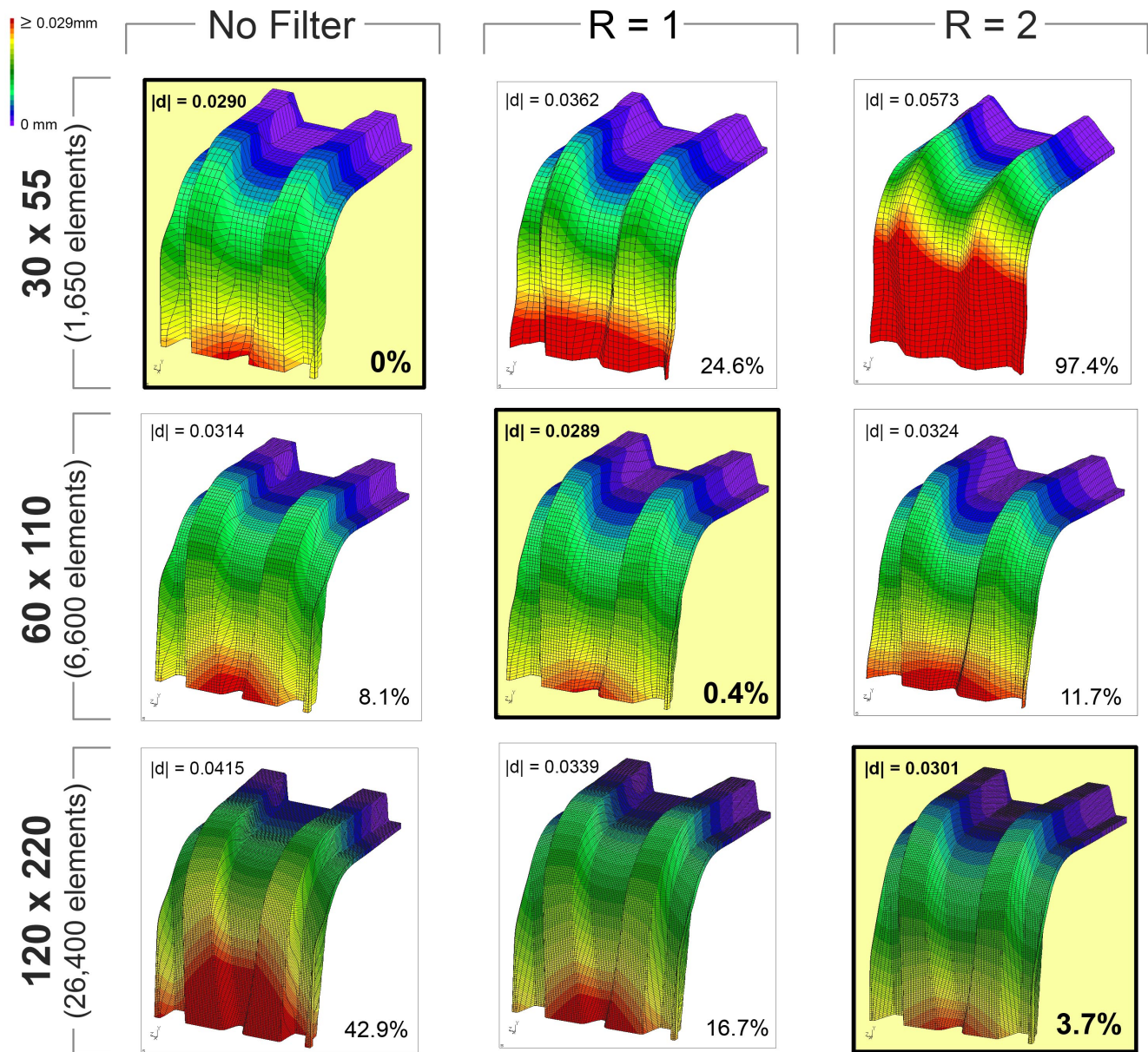


Figure 7. Percentage error and absolute error between the displacement of evolved solution (30 x 55 with no filter) and different resolutions with different smoothing ranges. Coordinating resolution changes with the size of smoothing influence produces very small differences between designs. By demonstrating that we achieve very similar mechanical performance using finer mesh discretization with more regular mesh elements, we evidence that our evolved solutions are not exploiting mesh irregularities to produce deceptive mechanical performance.

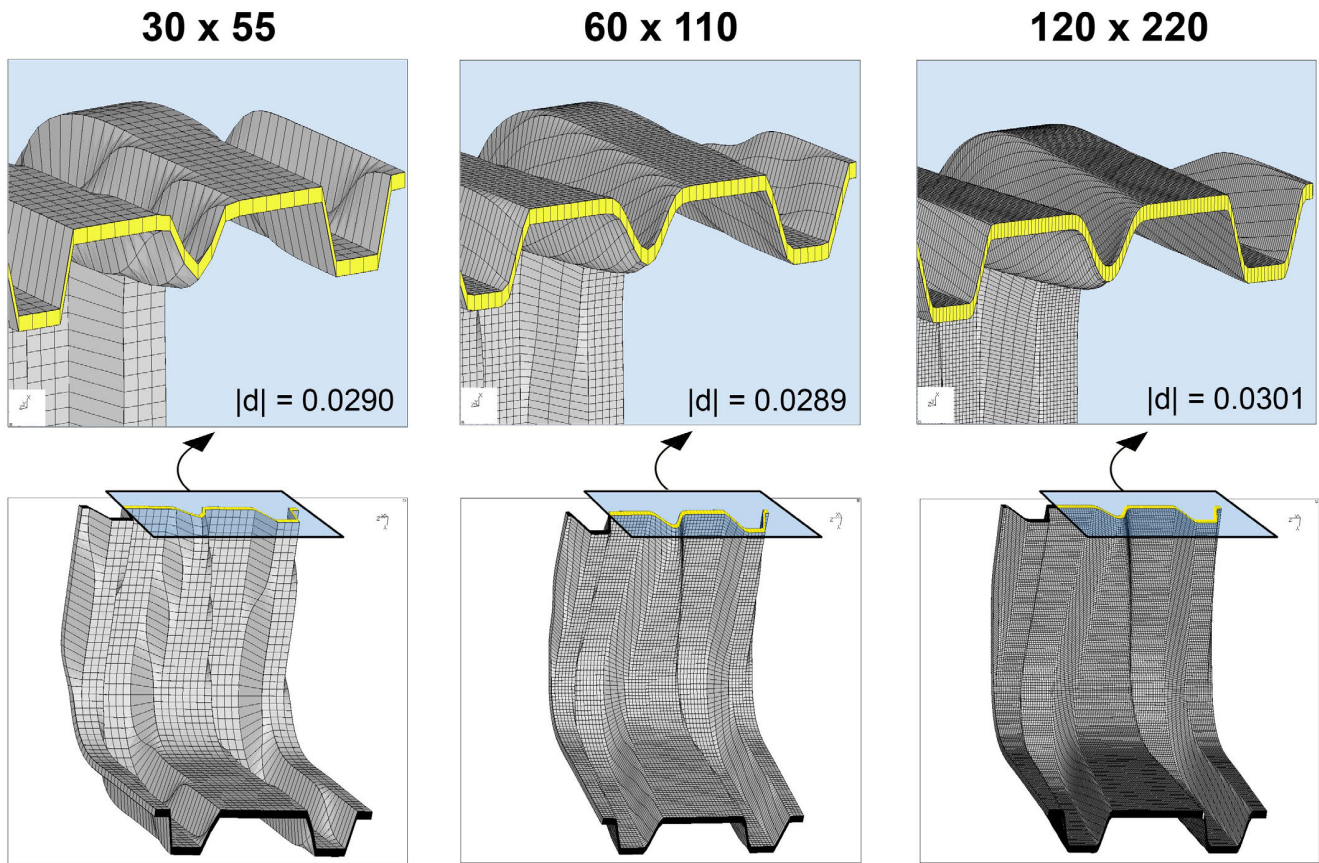


Figure 8. Mesh independence example. Increasing resolution and regularity of mesh elements does not alter physical performance.

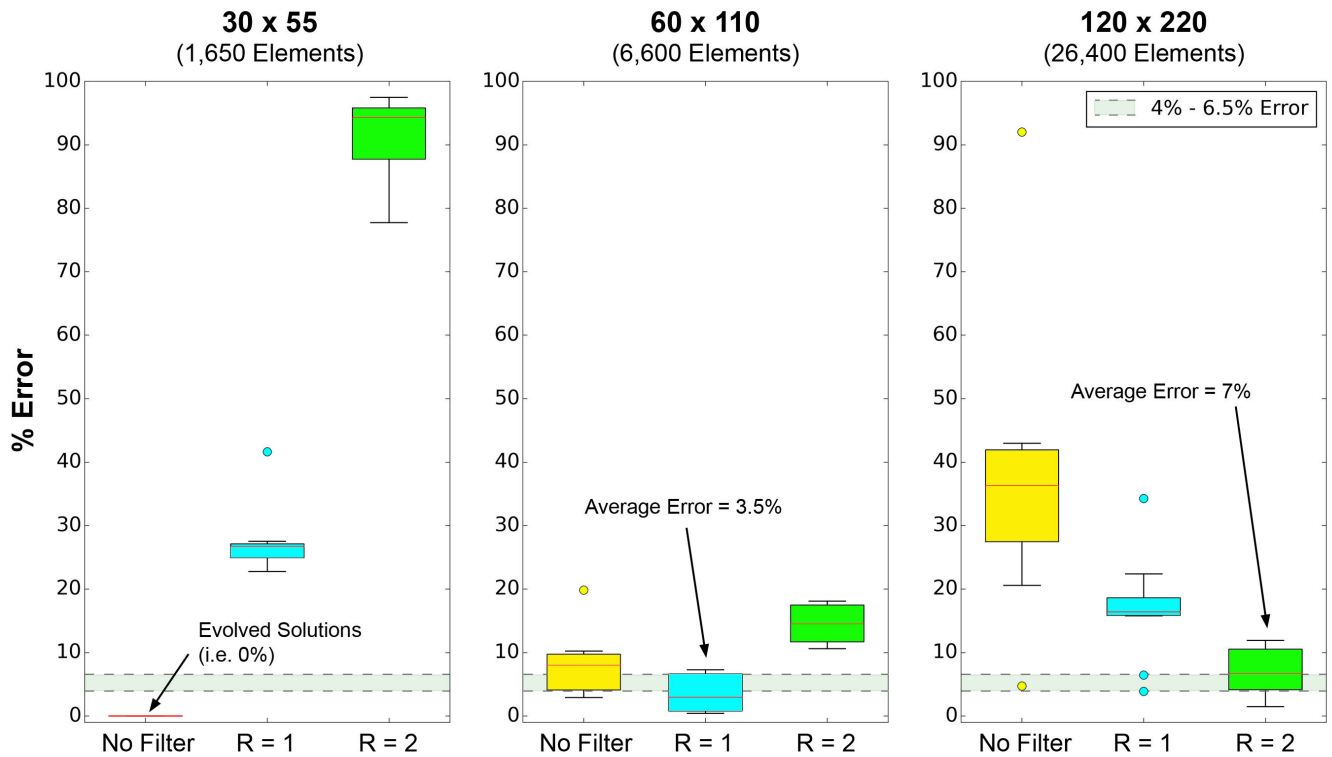


Figure 9. Percentage error incurred by scaling FE-meshes. Evolved solutions (i.e. 30 x 55 with no filter) have zero error because they set the performance benchmark. Percentage error within the range 4% - 6.5% is considered a good indicator that the solution is *mesh independent* [13].

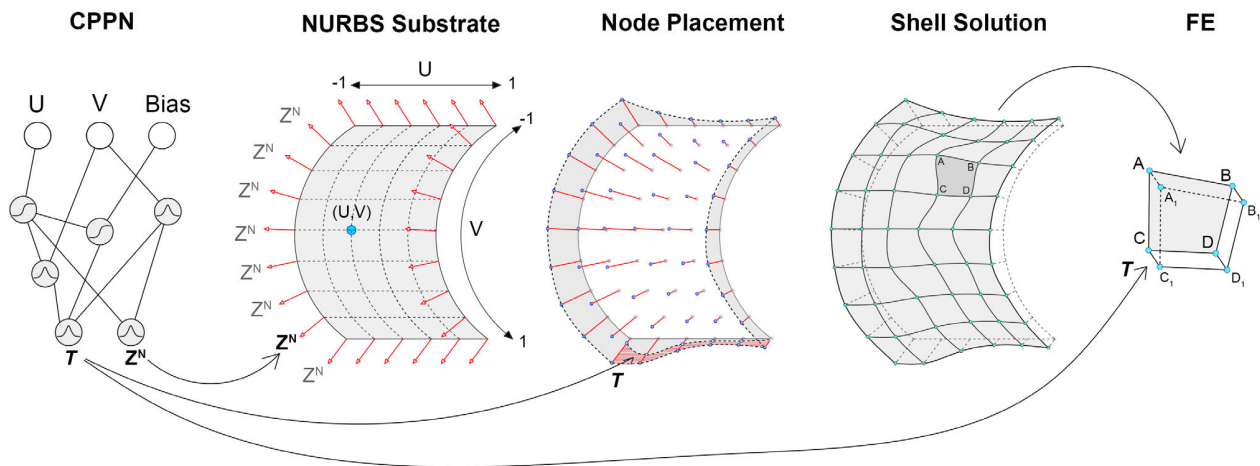


Figure 10. Surface manipulation process. Firstly, a CPPN queries each point within a NURBS-based substrate of specified discretization, and using the points (u,v) coordinates as inputs, returns a bead height (Z^N). Secondly, shell nodes are placed by extruding points in the direction relative to their surface normal by their CPPN generated bead height. To create localised shell thickness, points are then the interior face of the shell is extruded in the opposite direction to the surface normal by the value T , which is a value between 0.01 and 1.0. Shell solutions are then created by meshing the nodes. Finally, solutions are broken down into finite elements (FE) for structural analysis. Here the shell thickness of each FE is defined by controlling the distance between nodes A and A_1 .

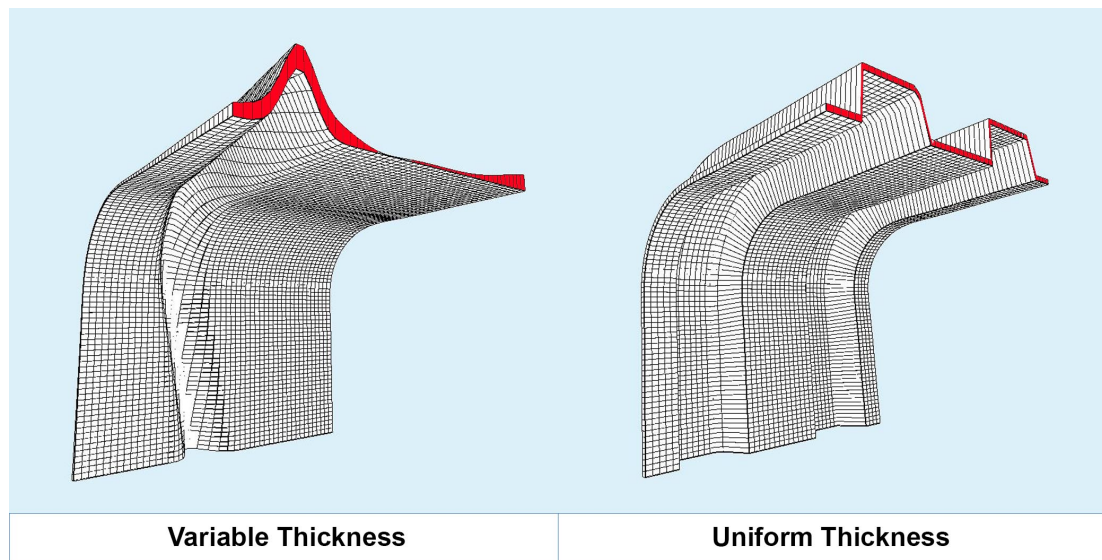


Figure 17. Observed geometric and formal differences between evolved solutions with a fixed (uniform) shell thickness and a variable shell thickness. Note that the variable thickness shell does not use more material; it simply has more control over how material is distributed.

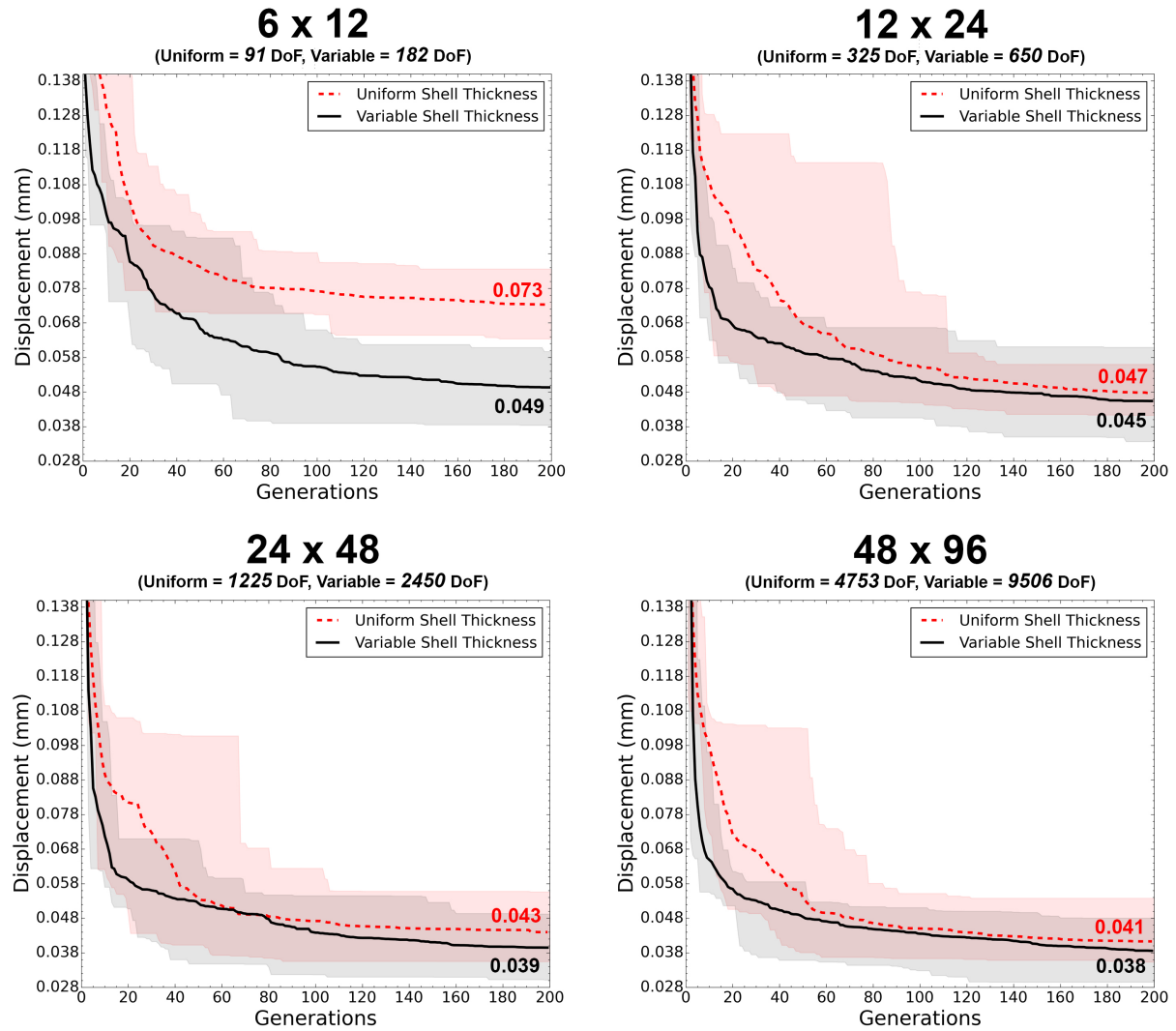


Figure 15. Convergence comparison of solutions with uniform and variable shell thickness. Mean convergence of the best solution in each population, at each generation, over 20 runs of the model, is shown. Also shown are the range of solutions found over all 20 runs. Solutions with variable shell thickness, which have double the number of DoF compared to solutions with uniform shell thickness, converge to superior solutions in fewer evaluations.